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HECTIC-II, COMPUTER PROGRAM FOR HEAT TRANSFER ANALYSIS OF GAS OR LIQUID COOLED REACTORS

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I. INTRODUCTION

Many computer programs have been developed during the last few years for the analysis of heat transfer in rod bundles; important examples are HECTIC [1, 2], MANTA [3], HAMBO [4, 5] and COBRA [6, 7, 8]. Of these, HECTIC and MANTA apply to single phase liquids only, while the HAMBO and COBRA programs have been extended to two-phase liquids as well. An excellent survey on existing computer programs and on programs under development has been given by Todreas and Wilson [9].

The purpose of the present paper is to show how the HECTIC-II code developed for an IBM 7090 computer is adapted to ICL-1905 computers in FORTRAN language. HECTIC-II calculates the pressure drop along the coolant channels, axial flow rates, heat transfer rates, rod surface and coolant temperatures in gas - cooled or single - phase liquid-cooled reactors.

The main features of the code can be summarized as follows:

a/ A typical "lumping" procedure is used in preparing input data. First, a symmetry is chosen to reduce a multirod fuel bundle to a minimum symmetry sector. Second, this selected sector is arbitrarily divided into parts, each part containing subchannels and heated surfaces;

b/ The program is founded on the basic principle of energy balance. Energy balance is obtained as a set of ordinary differential equations, which is solved by an n^{th} order Adams difference method;

c/ The code is extremely flexible. It can be used to analyse heat transfer of subchannels with widely varying geometries;

d/ Turbulent heat and momentum exchange between subchannels are considered;

e/ The code solves steady-state thermal-hydraulic problems only, and it can be applied correctly only when there is turbulent subsonic flow in the system being considered;

f/ A comparison of analyses and data reported in the literature shows that the lumped parameter or finite difference type of analyses that are used by HECTIC-II can yield fairly accurate predictions of canning temperatures [10], however, the coolant mixing predictions suggested by Kattchee and Reynolds are not very satisfactory [11].

Program's history: The original HECTIC computer program was developed for gas-cooled nuclear reactors only [1]. The second version of HECTIC is suitable for heat transfer analysis of liquid-cooled reactors, too [2, 12]. Subsequently developed HECTIC versions incorporate many important modifications [13, 14, 15].

II. GENERAL DESCRIPTION OF THE CODE

1. Fundamental equations

a/ Fluid flow calculation

HECTIC-II divides the total coolant flow through prescribed subchannels on the assumption that the pressure drops along all subchannels are identical. Friction, drag against spacers, acceleration, and turbulent momentum eddy exchange between adjacent subchannels are considered in the calculations. The equation for pressure drop in each subchannel is obtained from a momentum analysis on the fluid in a flow tube, and is

$$\Delta P_k = \left(P_{in} - P_{out}\right)_k = \frac{\rho_{av} V_k^2}{2 g_c} \left\{ 4 \cdot f_k \frac{L_k}{D_k} + \frac{A_{fs,k}}{A_{c,k}} \cdot C_{DS} + \right.$$

$$\left. + 2\left(\frac{\rho_{av}}{\rho_{out}} - \frac{\rho_{av}}{\rho_{in}}\right) + \sum_{i=1}^{N} \left[\mu . \mathrm{YEDM} \cdot \frac{\left(\frac{\varepsilon_i}{\nu} + \frac{\varepsilon_k}{\nu}\right)}{2 g_c} \cdot C_{i,k} \frac{L_k}{A_{c,k}} \left\{ V_k - V_i \right\} \right] \right. . \qquad /1/$$

This equation is solved by the subroutine SOLVE.

b/ Power calculations

Assuming axial power distribution, a relative power fraction is specified for each surface. The total power distribution on the j^{th} surface can be written in the form

$$P_j(x) = PF_j \cdot NF_j(x) \cdot KW \qquad /2/$$

c/ Surface temperature calculations

The heat transfer calculations cover four basic heat transfer modes:

1. Surface-to-coolant convection;
2. Intersurface radiation exchange;
3. Intersurface conduction;
4. Surface-to-environment heat loss.

For steady-state conditions, the total power generation per unit length at each point on the j^{th} surface must be equal to the heat transfer by all mentioned modes; thus:

$$q'_j = \sum_{i=1}^{N} h_i b_{i,j}(t_j - t_i) + \sum_{\ell=1}^{M}\left[\sigma \cdot REF_{j,\ell} \cdot P_j\left(T_j^2 + T_l^2\right) \cdot \left(T_j + T_l\right)\right] \cdot$$

$$\cdot\left(t_j - t_e\right) + \sum_{\ell=i}^{M} K_{j,l}\left(t_j - t_e\right) + GA_j\left(t_j - t_a\right). \qquad /3/$$

This is solved by the subroutine SOLVE.

The fluid and surface temperatures are calculated as a function of distance downstream from the inlet. The coolant temperature in the first length step is given as an input, but for subsequent length steps the coolant temperature is calculated from the differential equation of coolant temperature rise /see below/.

d/ Coolant temperature calculations

The differential equation for the coolant temperature rise is

$$W_i\, C_p \frac{dt_i}{dx} = \sum_{j=1}^{M} h_i b_{i,j}\left(t_j - t_i\right) + YEDH \cdot C_p \cdot \mu \sum_{k=1}^{N} \frac{\left(\frac{\varepsilon_i}{\nu} + \frac{\varepsilon_k}{\nu}\right)}{2} \cdot C_{i,k} \cdot \left(t_k - t_i\right) \qquad /4/$$

The set of simultaneous differential equations is solved by a sophisticated integration procedure.

2. Special features of HECTIC-II

In the HECTIC-II program the axial mesh size is automatically selected to ensure a prescribed accuracy of results obtained by the Adams predictor--corrector difference method.

The reactor core is divided into a number of axial sections, each section constituting a separate problem. It is supposed that the inlet temperatures for each subchannel are equal to the outlet temperatures of the previous section.

III. USER'S MANUAL

1. Input preparation

Input data are punched on paper tape or on cards. The expression "card" will be used for one record /i.e. one line/ of the paper tape.

Identification card: FORMAT /15A8/

The headings provide information for the user and machine operator. This card should follow the DATA card and precede only the first problem of a problem block.

Paramater card: FORMAT /1I1, 1F10.6, 4I10, 10X, 10I1/

Char.1 : C — The amount of data to be loaded for the problem is specified /one digit/ according to the following schedule:

Digit	Option
o	Read entire input.
1	Read PFJ, GAJ, and EMJ cards.
2	Read EMJ cards only.
3	Read GAJ cards only.
4	Read PFJ cards only.
5	Read normalized flux cards and inlet fluid temperatures.
6	Read the two operating input cards only.
7	Read the two input constants cards only. C must always be zero for the first problem. In subsequent problems having a value of C other than zero, the input data are values retained from the previous problem and the necessary new data.

char. 2 to 11: Problem number,

char.12 to 21: N, Number of subchannels.

char.22 to 31: M, Number of surfaces.

N and M integers must be loaded with the unit digit in the last column of the respective field, the remainder of the field being left blank. The code can handle up to 30 subchannels and 24 surfaces, for which it requires a memory capacity of 32 K words.

char.32 to 41: ITO, Inlet temperature options. These are specified by a one--digit integer in column 41, and offer the following choices:

Digit	Option
0	All inlet temperatures are set equal to TIN by the code.
1	Inlet temperatures are those given in the data sheet for the one-dimensional array TINI/I/.
2	Inlet temperatures for each passage of the program are set equal to the outlet temperatures of the previous problem, provided N is equal in both problems.

char.42 to 51: NFQ, Normalized flux option. This option permits the following program choices:

Digit	Option
0	The axial flux distributions on all surfaces of the problem are identical; only 21 values are needed in the ENFJX/J,K/ array.
1	The axial flux distributions are not identical on all surfaces; M x 21 values are needed in the ENFJX/J,K/ array.

char.62 to 71: NOPT, Print option. Columns 62 to 71 are used to indicate which data are to be printed. A digit 1 punched in the columns listed below causes the corresponding data to be printed out. Options not requested must be identified by 0 /they cannot be left blank/.

Column	Data
62	Input data /on the two input constants cards and the two operating input data cards/.
63	All one-dimensional arrays of input.
64	All two-dimensional arrays of input.
65	Computed quantities associated with each flow subchannel.
66	Normalized heat fluxes as a function of axial position.
67	Temperature. /If a zero is used in this column, temperature calculations are not carried out./
68	Zero for all problems.
69	Zero for all problems.
70	Monitor print of flow-rate iterations.
71	Monitor print of temperature iterations.

Input constants. FORMAT /1 F 11.0, 6 F 10.0/

Card 1.	GMW	Gas molecular weight /left blank or set as zero for liquid coolant/.
	EF	Exponent of Reynolds number in the friction factor equation

$$f = CF \cdot (R_e)^{-EF} \cdot YF \qquad /5/$$

	CF	Coefficient in the friction factor equation.
	EH	Exponent of Reynolds number in the Stanton number equation

$$St = CH \cdot (R_e)^{-EH} \cdot YST \qquad /6/$$

	CH	Coefficient in the Stanton number equation /nominally 0.023 $P_r^{-2/3}$/
	B1, B2	Constants in the specific heat equation

$$c_p = B_1 + B2 \cdot t \qquad /7/$$

Card 2.	B3, B4	Constants in the viscosity equation

$$\mu = B3 + B4 \cdot t \qquad /8/$$

	DLIQ	Liquid density /left blank or set as zero for gaveous coolant/.

Operating Inputs. /FORMAT /1 F 11.0, 6 F 10.0/

Card 1.	TIN	Mixed-mean coolant temperature at inlet.
	KW	Total power generated in all surfaces of the selected sector.
	W	Total coolant flow in selected sector.
	P	Inlet pressure.
	LF	Friction length of each subchannel.
	LH	Heated length of each subchannel.
	TA	Ambient temperature.
Card 2.	CDS	Spacer drag coefficient in the equation for spacer drag force

$$F_{sk} = A_{fsk} \cdot \frac{\rho_{av} (V_k)^2}{2g_c} \cdot CDS \qquad /9/$$

	YF	Friction factor adjusting factor.
	YEDM	Momentum eddy diffusivity adjusting factor.
	YST	Stanton number adjusting factor. By setting YST = 0, all heat transfer to the fluid is ignored. This artifice allows calculation of steady-state surface temperatures when the sole mechanisms of heat dissipation are conduction and radiation /to ambient sink/.
	YEDH	Heat eddy diffusivity adjusting factor.

ERMAX Maximum calculation error permitted in the Adams predictor-corrector scheme.

<u>One dimensional arrays.</u> FORMAT /1 F 11.0, 6 F 10.0/

Card 1. ENFJX/J,K/ Normalized local axial heat flux in the j^{th} surface for the K^{th} axial printing point, $1 \leq K \leq 21$ /In HECTIC-II the total length of subchannels in each problem is divided in to 20 equal parts; that is why there are 21 printing points in the program./

Card 2. TINI/I/ Inlet coolant temperature of the i^{th} subchannel.

Card 3. PFJ/J/ Power fraction of the j^{th} surface. The total of the power fractions must add up to unity.

Card 4. GAJ/J/ Conductance between the j^{th} surface and environment.

Card 5. EMJ/J/ Emissivity of the j^{th} surface. The value must be in the range from zero to unity.

Card 6. AI/I/ Flow area of the i^{th} subchannel.

<u>Two-dimensional arrays.</u> FORMAT /1 F 11.0, 6 F 10.0/

In two-dimensional arrays the first index denotes the row. The arrays are written in the program according to rows.

Card 1. CAYJL/J,L/ Intersurface conductances. This is a two-dimensional M x M array giving the thermal conductance between the j^{th} and l^{th} surfaces.

Card 2. FJL/J,L/ Radiation view factors. This is a two-dimensional M x M array giving the radiation view factor between the j^{th} and l^{th} surfaces. Note that the sum of the numbers in each row must be unity.

Card 3. BIJ/I,J/ Partial subchannel perimeters. This is a two-dimensional N x M array giving the wetted perimeter between the i^{th} subchannel and the j^{th} surface.

Card 4. CIK/I,K/ Mixing geometry factors. This is a two-dimensional N x N array; the value of CIK is defined by the ratio

$$\text{CIK/I,K/} = \frac{\text{perimeter of interface between subchannels } i \text{ and } k}{\text{nominal distance between subchannels } i \text{ and } k \text{ normal to interface.}}$$

<u>End-of-data card:</u> At the end of each set of data for a HECTIC-II problem, a card is written to indicate the end of input information. The card must have an integer 8 in column 1 if another

problem is to follow,or an integer 9 in column 1 if there are no more problems.

2. Code output

The output of HECTIC-II is self-explanatory for those who are familiar with its algorithm. Therefore, a brief summary of output results is sufficient. First, all input data are reprouced in the output.

The output data comprise the heat generation rates, surface temperatures, and coolant temperatures at the 21 printing points of the lumped subchannels and surfaces.

The group of calculated data resulting from flow calculations includes the following quantities:

PAS	Coolant subchannel index /i $\leq$ 30/
WI	Flow rate in the i^{th} subchannel
DI	Equivalent /hydraulic/ diameter of the i^{th} subchannel
REI	Reynolds number in the i^{th} subchannel
FFI	Fanning friction factor in the i^{th} subchannel
STI	Stanton number in the i^{th} subchannel
HI	Convection heat transfer coefficient in the i^{th} subchannel
ESI	The ratio eddy diffusivity /kinematic viscosity in the i^{th} subchannel.

The remaining calculated output values are printed in array format. They are

QPJ/J/	Absolute heat generation rate distribution in the j^{th} surface versus x/L_h for each surface j
TSJ/J/	Surface temperature distribution in the j^{th} surface versus x/L_h for each surface j
TGI/I/	Coolant temperature distribution in the i^{th} subchannel versus x/L_h for each subchannel i.

Additional useful information is printed out in a separate group as follows

TMM	Mixed-mean outlet temperature
PA	Total ambient loss to the ambient environment
PDROP	Pressure drop in each subchannel
NGTN	Number of coolant temperature modes employed
ERROR	Calculated coolant temperature error
EMACH	Calculated maximum Mach number.

3. Machine requirements

HECTIC-II program is written for ICL 1905 computers. The code requires a memory capacity of 32,000 words. The running time is determined by the complexity of the problem and the desired options, and is about 2-20 minutes, depending on actual number of surfaces and subchannels. The maximum number of surfaces and subchannels are: M = 24, N = 30, respectively.

Symbols and definitions

The unit system used for HECTIC computations follows in general the normally accepted engineering system.

Unit of mass = pounds
Units of length = inches and feet
Units of time = hours and seconds
Unit of temperature = ^{o}Fahrenheit.

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Physical or Mathematical Symbol	FORTRAN Symbol	Units	Definitions and Remarks
1.	2.	3.	4.
Ac	A	$inch^2$	total free flow area
Ac,i; AI	AI/I/	$inch^2$	free flow area in i^{th} subchannel
A_{fsi}; AFSI	AFSI/I/	$inch^2$	total frontal area of spacers in the i^{th} subchannel
B_1;B_2;B_3;B_4	B1;B2;B3;B4;	-	empirical constants in specific heat, and viscosity equation
b_i	PERI/I/	inch	total wetted perimeter of i^{th} subchannel
$b_{i,j}$; BIJ	BIJ/I,J/	inch	wetted perimeter between i^{th} subchannel and j^{th} surface
$C_{D,s}$	CDS	-	spacer drag coefficient, average for whole problem
CF; EF	CF; EF	-	constants in friction factor equation
CH; EH	CH; EH	-	constants in Stanton number equation
C_{ik}; CIK	CIK/I,K/	-	mixing geometry factor
C_p	CP	$Btu/lb_M/^{o}F$	average specific heat at constant pressure
D_i; DI	DI/I/	inch	hydraulic /equivalent/ diameter of i^{th} subchannel
$d_{i,k}$	-	inch	common perimeter of i^{th} and k^{th} subchannel
εj; EM_j	EMJ/J/	-	emissivity of j^{th} surface

1.	2.	3.	4.
ERMAX	ERMAX	^oF	maximum error permitted in mean temperature of coolant at outlet
ERROR	ERROR	^oF	maximum calculated coolant temperature error at outlet
f_i	FFI/I/	-	Fanning friction factor in i^{th} subchannel
F_{jl}; FJL	FJL/J,L/	-	radiation view factor between the j^{th} and l^{th} surfaces
F_{sk}	-	lb_F	spacer drag force
GA_j; GAJ	GAJ/J/	Btu/hr/ft/^{o}F	conductance between j^{th} surface and ambient environment
g_c	-	32.2 ft.lb_M/sec^2.lb_F	constant in Newton's Law
h_i; HI	HCI/I/	Btu/^{o}F/hr/ft^2	heat transfer coefficient in i^{th} subchannel
k	-	Btu/^{o}F/hr/ft	conductivity
K_{jl}	CAYJL/J,L/	Btu/^{o}F/hr/ft	intersurface conductance
KW	KW	kw	total power input
L_f; LF	ELF	inch	friction length of each subchannel
L_h; LH	ELH	inch	heated length of each subchannel
m	GMW	lb/lb_{mol}	molecular weight
M	EMACH	-	calculated Mach number
M	M	-	number of surfaces in problem /M $\leq$ 24/
N	N	-	number of subchannels in problem /N $\leq$ 30/

1.	2.	3.	4.
$NF_j/x/$	ENFJX/J,K/	-	normalized axial heat flux distribution in j^{th} surface at $x = K;\ 1 \leq K \leq 21$
i	ITO	-	inlet temperature option
NF	NFQ	-	normalized flux option
-	NOPT	-	print option
PDROP	PDROP	psi	pressure drop in each passage
PAS	PAS/I/	-	i^{th} coolant subchannel /printout only/
PF; PFJ	PFJ/J/	-	power fraction in j^{th} surface
P_{in}	P	psia	pressure at inlet
P_{out}	POUT	psia	pressure at outlet
P_j	PJ/J/	inch	perimeter of j^{th} surface
P_j	QPJP/KX,J/	Btu/hr/ft	absolute local heat flux in j^{th} surface for printing at node point KX
$P_j/x/$	QPJ/J/	Btu/hr/ft	absolute heat generatio- rate distribution in j^{th} surface
q'_{AMB}	PA	KW	total ambient heat loss to the ambient environment
			$q'_{AMB} = \sum_{j=1}^{M} \int_{o}^{L_n} GA_j \cdot (t_j - t_Y)\, dx$ /10/
R	-	$1545 \cdot \frac{ft.lb_F}{lb_{mol} \cdot R}$	universal gas constant
Re	RE/I/	-	Reynolds number in i^{th} subchannel : $Re = \frac{4.W}{b.u}$ /11/

1.	2.	3.	4.
$REF_{j',l}$	REFJL/J,L/	-	radiation exchange factor
St	STI/I/	-	Stanton number in i^{th} subchannel $St = \frac{h.Ac}{Cp.W}$
t	-	^oF	temperature /in general/
t_a; TA	TA	^oF	temperature of ambient environment
t_i	TGI/I/	^oF	coolant temperature in i^{th} subchannel
$t_i/x/$	TGIP/KX,I/	^oF	local coolant temperature in i^{th} subchannel for printing at node point KX
t_{in}	TIN	^oF	coolant temperature at inlet for all subchannels /mixed mean/
t_{out}	TOT	^oF	preliminary estimate of mixed-mean coolant temperature at outlet
T_j	TSZJ/J/	^oR	absolute temperature of j^{th} surface
t_j	TSJP/KX,J/	^oF	local temperature of j^{th} surface for printing at node point KX
t_k	TGI/K/	^oF	coolant temperature in k^{th} subchannel
T_l	TSZJ/L/	^oR	absolute temperature of l^{th} surface
TMM	TMM	^oF	mixed-mean coolant temperature at the outlet
$t_{s,j}$	TSJ/J/	^oF	average temperature of j^{th} surface
V_i	VSI/I/	ft/sec	average velocity in i^{th} subchannel
V_{in}	-	ft/sec	coolant velocity at inlet
V_{out}	-	ft/sec	coolant velocity at outlet

1.	2.	3.	4.
W	W	lb_M/hr	total coolant flow rate
W_i	WI/I/	lb_M/hr	flow rate in i^{th} subchannel
x	X	-	axial coordinate
YEDH	YEDH	-	heat eddy diffusivity adjusting factor
YEDM	YEDM	-	momentum eddy diffusivity adjusting factor
YF	YF	-	friction adjusting factor
YST	YST	-	Stanton number adjusting factor
μ	VIS	$lb_M/hr/ft$	average absolute viscosity
ρ_{av}	DAV	lb_M/ft^3	average density: $\rho = \frac{Pin \cdot m}{R \cdot Tin}$ for a gas /12/ ρ = constant for a liquid
ρ	DLIQ	lb_M/ft^3	density of coolant, when a liquid
μ_{turb}	-	$lb_M/hr/ft$	turbulent absolute viscosity $\mu_{turb} = \epsilon \cdot \rho$ /13/
ρ_{in}	DIN	lb_M/ft^3	coolant density at inlet
ρ_{out}	DOT	lb_M/ft^3	coolant density at outlet
ν	-	ft^2/hr	kinematic viscosity
ϵ	-	ft^2/hr	eddy diffusivity
$\tau_{p,ik}$	-	psia	interpassage turbulent shear between the i^{th} and k^{th} subchannels
δ_{ik}	-	inch	distance between the nominal centroids of i^{th} and k^{th} subchannels

1.	2.	3.	4.
ϵ_i/ν	ESI/I/	-	eddy diffusivity/kinematic viscosity in i^{th} subchannels
$\tau_{w,k}$	-	psi	wall shear stress in k^{th} subchannel
T_{in}	-	^{o}F	absolute temperature at inlet $T_{in} = t_{in} + 460$

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